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ORBSCAN Accuracy in Measuring Corneal Surface Elevation

Aircrew Health and Performance Division

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Purpose. The Surgeon General has recently authorized individuals who have had corneal refractive surgery entry, by waiver, into the services. Since Army aviators already operate under less than optimal visual conditions, the eyes are working at the limits of the visual and optical system. Changes to the optical system must be very accurately assessed to determine impact on vision, and measurement of the cornea is the primary means of verifying the optical characteristics of an eye after refractive surgery. A measurement error of less than ±1.0 micrometers is difficult to attain, so an independent assessment of the instrument's accuracy and repeatability is a fundamental prerequisite to corneal topography analysis. This was the research objective in this study. Methods. Two types of corneal topography instruments were used in this study; they included 1) a videokeratoscope, EyeSys Corneal Analysis System 2000, and 2) a corneal profile topographer, the ORBSCAN, manufactured by ORBTEK. A cornea was measured whose shape closely matched one of the EyeSys calibration objects. Using the living cornea as a calibration surface with known topography, we measured it with the ORBSCAN.

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Differences between the EyeSys and ORBSCAN surface elevation measurements were interpreted as ORBSCAN error. **Results.** For most of the measured cornea (5.4-mm zone),EyeSys repeatability was 0.50 μm or better. ORBSCAN repeatability was between 1-2 μm for most of the cornea. As with repeatability, accuracy with the EyeSys is best near the corneal center and gets worse peripherally. After compensation, EyeSys error is reduced to better than 0.5 μm across most of the 5.4-mm corneal zone. The ORBSCAN underestimated the surface elevations of the cornea, and the magnitude of the error was much larger than that of the EyeSys either before or after correction for instrument bias. Measurement error showed a steady increase from center to periphery, with maximum errors exceeding 10 μm. **Discussion.** Both the ORBSCAN and EyeSys underestimated surface elevation, and errors increased peripherally. The ORBSCAN error was generally twice as large as the raw EyeSys error. After compensation for known instrument error, EyeSys accuracy improved substantially, and this improves the accuracy of this videokeratoscope to the desired level (<1 μm error) within most of the 5.4-mm diameter corneal zone. The EyeSys was also about three times more precise than the ORBSCAN for repeated measurements of a normal human cornea.

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Introduction

Research context

The human eye can be thought of as a living optical sensor that acquires images and relays the data to the brain for processing and analysis (Horton, 1992). Vision provides us with more information than any of the other senses. This is reflected in the fact that approximately half of the cerebral cortex is involved in processing visual information (Kandel, 1995; AOA News, 1999).

The visual process (Fig. 1) begins with the formation of an optical image on the retina by the eye's two lenses, the cornea and crystalline lens. The cornea forms the front surface of the eye, and since it provides about 70% of the eye's refractive power, the cornea is the eye's most important lens. Good vision depends on good retinal image quality, and this in turn depends on good optical quality of the cornea and lens. Refractive error of defocus, such as myopia (near sightedness), hyperopia (far sightedness) or astigmatism, are common optical defects. Fortunately, defocus errors are easily corrected by adding a spectacle or contact lens to the eye's optical system. Most eyes have additional, subtler refractive errors, which are referred to as the higher order aberrations. In clinical practice these are ignored, since their effect on image quality is usually insignificant compared to the errors of defocus. This is fortunate because, until recently, it was extremely difficult to measure these aberrations, and there was no practical way to fabricate a lens that could correct these complex optical defects (Miller, 2000).

Figure 1. Visual process. In the first stage of the visual process, data about the scene are optically transferred to the retina; from there, neurons transmit the data to the brain where complex image analysis and processing produces our sense of vision.

Another way to correct refractive errors is to reshape one of the eye's lenses into a new lens of the appropriate power. Since the cornea is the eye's most important lens and is easily accessible, it is the ocular lens that is modified during most refractive surgeries. The two most popular surgical techniques, photorefractive keratectomy (PRK) and laser assisted in-situ keratomileusis (LASIK), use a high-energy laser to ablate (vaporize) portions of the corneal surface and thereby reshape it into a new lens of the proper power to correct errors of defocus. The Food and Drug Administration (FDA) first approved the use of PRK to correct myopia in October 1995 and LASIK was approved in November

1998. The laser correction of astigmatism and hyperopia have only recently been approved.

Refractive surgery is rapidly becoming one of the popular ways to correct errors of defocus. It is appealing since it is designed to correct the optics of the eye itself and reduces the patient's dependence on external lenses (spectacles or contact lenses). Refractive surgery however is still relatively new and is far from perfect. Spectacles and contact lenses correct defocus errors while leaving the naturally small higher order aberrations essentially unchanged. Current refractive surgeries, however, alter the eye's aberrations while attempting to correct defocus, and in some cases, leave the patients with degraded vision that cannot be corrected with either spectacles or contact lenses (Maguire, 1994; Halliday, 1995; Schwiegerling and Snyder, 1998). The key to eliminating unwanted aberrations in refractive surgery is to properly ablate the corneal surface to compensate, not only for errors of defocus, but higher order aberrations as well.

One of the most direct ways to evaluate surgically induced optical effects is to measure corneal topography before and after surgery. Recently, several instruments have been developed to measure corneal topography, but a key question is, are they accurate enough to allow computation of the cornea's optical aberrations? In order to measure the subtle surface anomalies that can cause visually significant optical aberrations, these instruments should have an absolute measurement error of less than ± 1.0 µm (Applegate et al., 1995, Horner and Salmon, 1998). This level of accuracy is difficult to attain, so it is questionable whether most of today's corneal topography instruments are sufficiently accurate to study corneal aberrations. A fundamental prerequisite to corneal topographic analysis, using instruments such as the ORBSCAN, is an independent assessment of the instrument's accuracy and repeatability. This is the research objective in this study.

Military significance

Refractive surgery is becoming a popular method for correcting refractive error in the civilian sector. When PRK was first FDA approved in 1996, approximately 250,000 procedures were performed. By 1999, the annual refractive procedure rate had risen to 750,000, however less than 100,000 of these procedures were PRK, most were LASIK (Beiting, 1999). The annual number of procedures is expected to reach 1 million in the year 2000. The Army will be faced with an increasing population of soldiers who have either had or are considering refractive surgery. Reports in the public media create the impression that excellent vision can always be expected from refractive surgery, yet its optical effects on operational performance in a military setting have been investigated only superficially.

The military is interested in refractive surgery because it offers a mode of refractive error correction that potentially eliminates the man-machine interface problems of spectacles. Spectacles have been shown to cause compatibility problems with

sophisticated head mounted information displays (HMDs), such as the Integrated Helmet Display and Sighting System (IHADSS) in the AH-64 Apache helicopter (Lattimore, 1990). The Army is steadily increasing the number of weapons systems that rely on HMDs to provide critical information to the operator. Spectacles will therefore become more of a difficulty as these systems are fielded. Contact lenses can solve the equipment compatibility problem, however only 72% of pilots requiring refractive correction were successfully fit with contact lenses in a study evaluating only two contact lens options for Apache pilots (Lattimore, 1992; Lattimore and Cornum, 1993). Although a greater percentage may be fit with contact lenses through improved contact lens designs and options, more logistical and medical support is needed to sustain contact lens wear in a tactical environment than is needed to support soldiers who have had refractive surgery.

Refractive surgery is an option that has heretofore been unacceptable in the military environment. The earliest refractive surgery procedure, radial keratotomy (RK), results in adequate high contrast visual acuity (HCVA) in most cases. However, an HCVA of 20/20 can be obtained even though RK often causes a compromised cornea prone to significant curvature fluctuations and unable to withstand the effects of altitude and trauma (Schanzlin et al., 1986; Binder et al., 1988; Enzenauer et al., 1993; Bullimore et al., 1994; Mader et al., 1996; Ng et al., 1996). With the advent of PRK and LASIK, many of the undesirable consequences encountered with RK have been eliminated. Recently, the Surgeon General has authorized individuals who have had PRK or LASIK entry into the services with a waiver. Individuals already in the service who have PRK or LASIK must be able to meet retention standards after the procedure (AR 40-501). These procedures are still not allowed in certain combat-related specialties, however, including aviation.

The Army aviation environment is more visually demanding than that found in most of the civilian sector. Army aviators operate routinely under less-than-optimal visual conditions, including low contrast and low luminance, therefore the eyes are working at the limits of the visual and optical system. Given that refractive surgery does not alter the neural mechanisms of vision, from the retina to the visual cortex, changes to the optical system must be very accurately assessed to determine the impact on vision. The cornea is the primary refractive surface of the eye, therefore measurement of the cornea is one of the primary means of verifying the optical characteristics of an eye after refractive surgery.

The U.S. Army Aeromedical Research Laboratory can provide the Army with important research on the optical results of refractive surgery. The Visual Sciences Branch of the Aircrew Health and Performance Division is equipped with several technologically advanced instruments for measuring corneal topography, including one representative from each of the two major subcategories of corneal topographers, the EyeSys and the ORBSCAN.

Corneal topography instruments

Two categories of corneal topography instruments are commercially available today (Mandell, 1996). They are the 1) videokeratoscopes and 2) corneal profile topographers. Computerized videokeratoscopes are the most widely used clinical corneal topography instruments, with at least seven different commercial products available today (Horner, Salmon, and Soni, 1998). These instruments compute the corneal surface shape indirectly by analyzing an optical image reflected off the corneal surface. The Vision Branch has one of the most popular videokeratoscopes, the EyeSys Corneal Analysis System 2000 (Fig. 2). USAARL Report No. 98-29 (Salmon, Rash, and Mora, 1998) reports on the accuracy of this instrument and its potential use in military vision research.

Figure 2. The EyeSys Corneal Analysis System 2000. This system analyses the reflected image of a target that consists of concentric black and white rings. Corneal measurements and raw data are therefore organized on a polar sampling grid. (Photo from EyeSys Vision Group)

By using an entirely different operating principle from the videokeratoscopes, corneal profile topographers attempt to measure the surface contour of the cornea more directly. Very few instruments of this type have been produced; among them, the ORBSCAN, manufactured by ORBTEK, Inc. (ORBTEK, 2000) has been attracting considerable interest from refractive surgeons because of its unique capabilities. While videokeratoscopes measure only the front surface of the cornea, the ORBSCAN can map both the front and back surfaces, as well as measure thickness across the entire cornea. It has the potential to measure anterior chamber depth and the front surface of the

crystalline lens as well. Slit-scan technology allows the ORBSCAN to measure corneas with abnormal surface conditions that would prevent measurement with a videokeratoscope; for example, severely irregular, desiccated, or debrided surfaces. Finally, the slit-scan is able to measure the cornea dimensions without relying on mathematical assumptions about cornea shape such as those required by videokeratoscope algorithms (Applegate et al., 1995).

Among its disadvantages, the ORBSCAN is a large, expensive instrument. While most videokeratoscopes are tabletop instruments, and some hand-held versions are available, the ORBSCAN occupies approximately 12 square feet of floor space. It costs approximately $40,000, which is four times as much as a typical videokeratoscope. Since it takes 5 seconds to acquire a single data image, it may be more subject to error caused by eye movements, though the instrument is designed to minimize this effect by tracking eye movements during measurement. In comparison, the EyeSys captures one image in about 1/60 second. Finally, its accuracy is difficult to assess, and though its repeatability is generally considered adequate for clinical purposes, its accuracy for corneal optics research has been assessed only superficially. A limited in-house study of ORBSCAN accuracy is available from the manufacturer (Lundergan and Turner, 1996; Marmer and Turner, 1996), but a comprehensive literature search revealed no published articles describing the ORBSCAN's accuracy. The methods section explains why accuracy is more difficult to assess in the ORBSCAN than with videokeratoscope systems. Our research objective was to evaluate the accuracy of the ORBSCAN in measuring the elevation topography of the anterior corneal surface.

Methods

The problem with ORBSCAN calibration

Repeatability can be evaluated by studying the variance for repeated measurements of a human cornea. Accuracy, on the other hand, must be tested by comparing measurements to some "gold standard"—usually a model cornea whose exact dimensions are known (Mandell, 1996). Computerized videokeratoscopes measure corneal topography by using the specular reflective (shiny) properties of the corneal surface. Any specularly reflecting test object that models a normal cornea is an appropriate surface for testing videokeratoscope accuracy, and these are relatively easy to manufacture. Examples of commonly used videokeratoscope calibration surfaces are stainless steel ball bearings or polished plastic domes. A previous USAARL report (Salmon, Rash, and Mora, 1998), evaluated the accuracy of the EyeSys videokeratoscope by measuring a series of polished plastic surfaces that were designed to simulate a range of normal human corneas. Analysis of instrument error lead to the development of an error compensating algorithm that significantly improved measurement accuracy in the EyeSys. This reduced the maximum error in surface elevation measurements to less than 1.0 μm, which is the level of accuracy needed for corneal optics research.

Accuracy assessment with the ORBSCAN system is much more difficult because this instrument uses a unique method for measuring corneal topography that depends on partially diffuse reflections from within the cornea. Specularly reflecting test surfaces can provide a rough estimate of ORBSCAN accuracy, but do not allow formation of an intracorneal optical slit (Fig. 3), which is the fundamental operating principle used by the ORBSCAN. What is needed is a semi-transparent, partially diffuse reflecting test object with the same thickness, shape and optical properties of a normal human cornea. Unfortunately, such an object is very difficult to fabricate, and to date even the manufacturer, ORBTEK, has not developed a test surface that meets all these conditions.

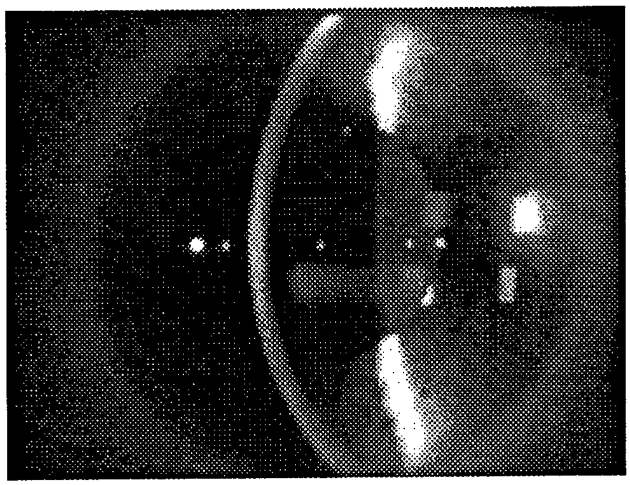

Figure 3. Example image showing 1 of 40 slits beams used by the ORBSCAN to measure corneal topography.

General approach

Since manmade calibration surfaces for directly assessing ORBSCAN accuracy are not available, we designed a two-step, indirect approach. First, after calibrating an EyeSys videokeratoscope using known plastic test surfaces, we measured a cornea whose shape closely matched one of the EyeSys calibration objects. Second, using this living cornea as a calibration surface with known topography (based on the EyeSys data) we measured it with the ORBSCAN. Differences between the EyeSys and ORBSCAN surface elevation measurements were interpreted as ORBSCAN error, for differences greater than the measurement accuracy of the EyeSys.

Raw EyeSys accuracy

Accuracy of the EyeSys videokeratoscope has been evaluated and reported in several recent studies (Horner and Salmon, 1998; Salmon, Rash, and Mora, 1998; Salmon, 1999). Following the same procedure described in those publications, we measured six rotationally symmetric ellipsoids designed to model the normal range of corneal

sizes. The polished polymethylmethacrylate (PMMA) test surfaces were manufactured by Sterling International Technologies and were guaranteed to conform to the specified elevation parameters to within ±1.0 µm, though company engineers stated that the surfaces had been verified using a Rank Taylor Hobson Talysurf, a stylus device with a resolution of better than 0.1 µm. Parameters of the six test surfaces are summarized in Table 1.

Table 1.
Parameters of the test surfaces used to calibrate the EyeSys videokeratoscope.

Surface ID	Apical radius (mm)	Shape factor (p)	Model description
78/05	7.8	0.5	flattening prolate cornea
78/07	7.8	0.7	average prolate cornea
78/10	7.8	1.0	spherical cornea
78/13	7.8	1.3	post refractive surgery cornea
73/07	7.3	0.7	steep corneal radius
83/07	8.3	0.7	flat cornea radius

Note: All were rotationally symmetric ellipsoids, whose rate of peripheral flattening was described by the shape factor (p). Shape factor (p) is equal to $1-e^2$, where e is the geometric eccentricity. Values of $0<p<1.0$ represent prolate ellipsoids; $p=1.0$ is a sphere and $p>1.0$ is an oblate ellipsoid.

Multiple EyeSys images were taken of each surface, and the best image was selected for analysis based on map centration, symmetry and accuracy of the measured apical radius. The measured surface elevation contour was compared to the known surface topography, and EyeSys measurement error at discrete locations was computed by Eq.(1).

$$\text{Error} = \text{measured} - \text{known} \qquad (1)$$

The EyeSys measures the cornea on a polar grid with 360 radial meridians (1 per angular degree) and 18 concentric rings spaced at approximately 0.25-mm intervals. (See instrument face in Fig. 2.) Because of the polar sampling and rotational symmetry of the test surfaces, each ring provided 360 measurements, at 18 distances from the center. The mean of 360 values associated with each ring was taken as the mean surface elevation at 18 distances from the center. Figure 4 shows the mean EyeSys error for surface elevation measurements for each of the six surfaces. Error increases with distance from the center, and depending on the surface, reaches a maximum error of approximately -2 to -6 µm. The negative sign indicates that the EyeSys tends to underestimate surface elevation.

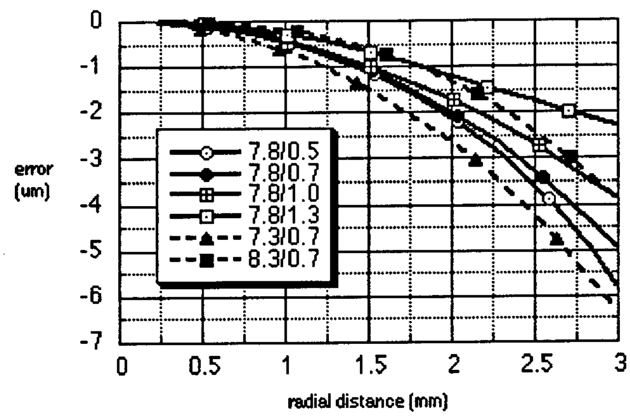

Figure 4. Raw EyeSys surface elevation measurement error as a function of distance from the center of six rotationally symmetric test surfaces. The legend shows the apical radius (first number) and shape factor, p (second number), for each surface. The EyeSys measures out to approximately 4.5-mm from the center, but for the purposes of this study, the region of interest is the central 3-mm radius, since this corresponds with the treatment zone in most refractive surgeries.

Algorithm to improve EyeSys accuracy

Analysis of the errors shown in Fig. 4 revealed a correlation between the magnitude of error and radial distance from the center, apical radius and shape factor. Two previous studies described a method to compensate for this pattern of measurement error within EyeSys (Horner and Salmon, 1998; Salmon, 1999). A similar error compensation algorithm, developed in this study, is summarized in the following paragraphs.

Step 1. Compute the apical radius and shape factor for each surface.

For every image, the EyeSys stores data in numerous computer files. One file contains the local radius of curvature (axial radius) at each sampled point and is designated by an ".xx" extension. Another contains the radial distance from the corneal center to each sampled point and is designated by an ".ra" extension. For each surface, mean axial radius and mean radial distance values corresponding to every EyeSys ring were computed. Table 2 shows an example of this data arrangement for one of the surfaces.

Table 2.

Mean radial distances and axial radii for each EyeSys ring for the test surface with apical radius of 7.8 mm and shape factor of p=0,5. Distances are in micrometers.

EyeSys ring	radial dist (ra)	axial rad (xx)
1	255.9	7838.5
2	512.8	7853.5
3	751.3	7872.6
4	1018.8	7886.2
5	1259.5	7906.4
6	1527.6	7924.2
7	1769.4	7951.7
8	2044.3	7983.7
9	2295.2	8023.2
10	2580.1	8068.6
11	2837.2	8122.0
12	3134.8	8178.9
13	3406.4	8240.0
14	3709.0	8309.2
15	3996.7	8384.5
16	4317.1	8467.4
17	4625.6	8536.7
18	4918.2	8586.4

In the case of conic sections, the axial radii (x_x) and radial distances (r_a) are related by the following equation, in which p is the shape factor and r is the apical radius of curvature (Douthwaite, 1995):

$$x_x^2 = (1-p)(r_a)^2 + r^2 \qquad (2)$$

This is a linear equation of the form, y = mx + b, in which x_x^2 may be plotted along the y-axis and r_a^2 along the x-axis. The slope of the best-fit linear regression is equal to (1-p), and the y intercept is equal to r^2.

$$p = (1\text{-slope}) \qquad (3)$$

$$r = \sqrt{(\text{y intercept})} \qquad (4)$$

Applying these relationships, the shape factor (p) and apical radius (r) for each surface were computed based on the EyeSys measurements.

Step 2. Correct the measured apical radius (r) for each surface

The apical radii, computed for each surface above, were slightly larger than the true apical radii. Plotting actual radius (y-axis) as a function of measured radius (x-axis), we

saw a close linear correlation between the two, and from this, we developed a simple formula to correct the measured EyeSys apical radii (r').

$$r' = 1.370r - 0.3386 \quad (5)$$

Step 3. Correct the measured shape factors (p) for each surface

Four of the test surfaces had the same apical radii, but differed in their shape factors (see Table 1). Plotting actual p value (y-axis) as a function of measured p value (x-axis), we saw a close linear correlation between the two, and from this we developed a simple formula to correct the measured EyeSys shape factors (p') for the surfaces with a 7.8-mm apical radius.

$$p' = 0.964p + 0.036 \quad (6)$$

Three of the test surfaces had the same shape factor, but different apical radii. Studying the error in measured p values for these surfaces, an addition correction was applied to correct the shape factor (p") for surfaces with any apical radius.

$$p'' = (3.821e\text{-}5)r' - 0.299 + p' \quad (7)$$

Step 4. Estimate EyeSys error as a function of radial distance from the center

EyeSys error increases as a function of distance from the corneal center, as shown in Fig. 3. Relative error, defined in Eq. (8), increases nearly linearly with distance from the center, and this makes it easier to compensate for the EyeSys error with a simple linear formula.

$$\text{relative error} = \text{error} / (\text{measured elevation}) \quad (8)$$

The slope and y intercept values for the equation to predict relative error (Eq. 11) vary as a simple function of shape factor (p") as shown in Eqs. (9, 10).

$$\text{slope} = (2.158e\text{-}6)p'' - 2.329e\text{-}6 \quad (9)$$

$$\text{intercept} = (3.755e\text{-}4)p'' - 6.192e\text{-}3 \quad (10)$$

$$(\text{relative error}) = (\text{measured elevation})(\text{slope}) + \text{intercept} \quad (11)$$

The estimated EyeSys surface elevation measurement error can then be computed from the estimated relative error by Eq. (12).

$$\text{EyeSys error} = (\text{relative error})(\text{measured elevation}) \quad (12)$$

Step 5. Correct measured EyeSys elevations

Finally, the EyeSys measurements can be corrected for the estimated instrument error by Eq. (13).

$$\text{corrected elevation} = (\text{measured elevation}) - (\text{EyeSys error}) \tag{13}$$

When this error correction algorithm is applied to the raw EyeSys measurements (Fig. 4), measurement accuracy improves significantly, as shown in Fig. 5. Within 3 mm of the corneal center, maximum error for the four surfaces with an apical radius of 7.8 mm was less than 0.25 μm. For the 8.3-mm-radius surface, maximum error was less than 0.5 μm, and for the surface that represented a very steep cornea (r = 7.3 mm), error was approximately 1.0 μm. This is similar to the level of accuracy reported in one study that tested another videokeratoscope, the Keratron (Tripoli et al., 1995). This established the degree of accuracy that we could expect when the EyeSys was used to measure surfaces that were similar in shape to our test objects.

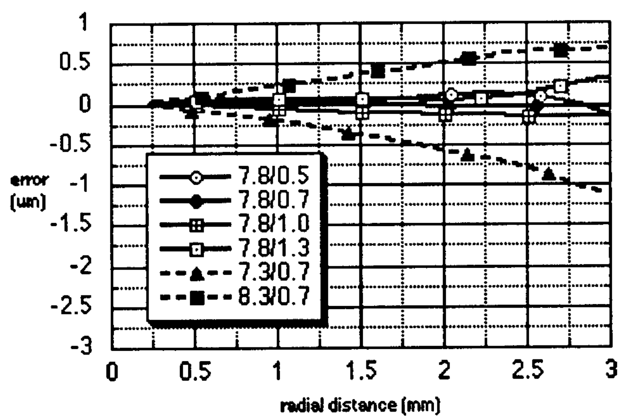

Figure 5. EyeSys error after compensation for instrument bias.

Subjects

We then needed to find a human cornea whose shape, as measured by the EyeSys, closely matched the parameters of one of our test surfaces. After taking EyeSys images of a number of persons, and obtaining informed consent, we decided to use, as our test cornea, the healthy, normal right eye of a female subject, age 39. Her apical corneal radius and shape factors were, respectively, 7.85 mm and p= 0.92. She had only 0.27 diopters of corneal astigmatism, and her corneal topography map showed little asymmetry. Several studies have shown that, for small amounts of corneal astigmatism,

accuracy is very similar to that obtained with rotationally symmetric surfaces (Greivenkamp et al., 1996, Klein, 1997).

Procedure to test ORBSCAN accuracy

Sixteen EyeSys measurements were taken of this cornea, and the data associated with each image were corrected for systematic instrument error according to the algorithm described above. The mean of 16 sets of corrected surface elevation data was taken as the true elevation topography of this cornea, within the measurement accuracy of the EyeSys.

During the same experimental session, lasting approximately 3 hours, 16 measurements of the same cornea were made using the ORBSCAN. The mean of 16 sets of surface elevation data was taken as the ORBSCAN estimate of the elevation topography of the same cornea.

Since the accuracy of the EyeSys was known, and the test cornea was very close to our calibration surfaces, we treated the EyeSys data as the "gold standard" to which the ORBSCAN measurements could be compared for accuracy. Because portions of some data images were missing, comparison was limited to a circular zone within a 2.7-mm radius of the corneal center (5.4-mm diameter corneal zone).

A direct comparison of the EyeSys and ORBSCAN data is not possible because these instruments sample the corneal at different discrete locations. EyeSys raw data are organized on a 360 x 18 polar grid, while the ORBSCAN data were arrayed in a 0.1-mm square Cartesian grid. Both data sets were therefore fitted to Zernike polynomials (Schwiegerling, Greivenkamp, and Miller, 1995), and then, using the Zernike coefficients, both EyeSys and ORBSCAN topographies were reconstructed to a common grid. Prior to the reconstruction, the Zernike modes representing tilt were removed from both data sets to eliminate any differences the line of sight alignment between the two instruments. Finally, the mean reconstructed EyeSys and ORBSCAN surface elevation data were compared.

Results

The following results describe the repeatability and accuracy for surface elevation measurements of a 5.4-mm diameter corneal zone, that is, within a 2.7-mm radius of the corneal center. Repeatability is shown by contour/gray scale plots of the standard errors for 16 measurements of the same human cornea by the EyeSys and ORBSCAN, in Figs. 6 and 7, respectively.

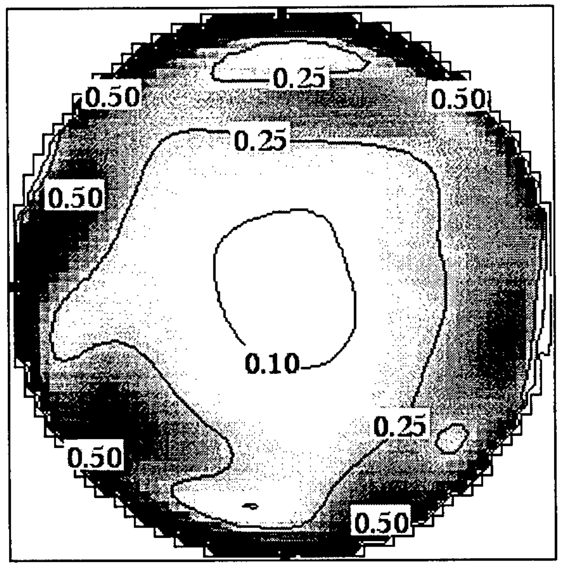

Figure 6. EyeSys repeatability. Repeatability is expressed as the standard error of 16 surface elevation measurements of a human cornea. Labels and contour lines are in micrometers, and the map shows a 5.4-mm corneal zone.

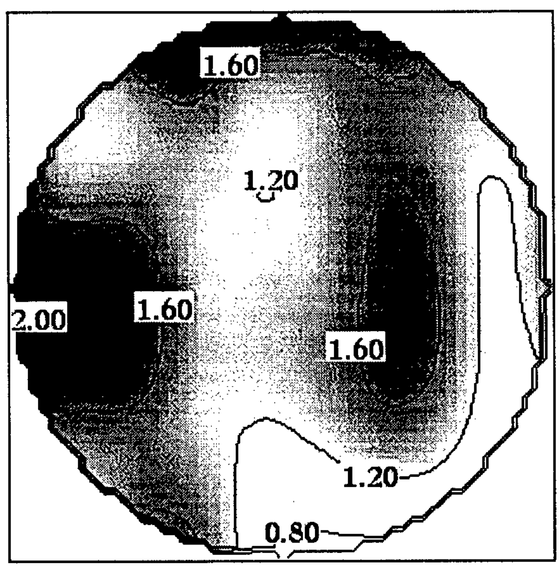

Figure 7. ORBSCAN repeatability. Repeatability is expressed as the standard error of 16 surface elevation measurement of the same human cornea shown in Figure 6. Labels and contour lines are in micrometers, and the map shows a 5.4-mm corneal zone.

For most of the measured cornea (5.4-mm zone), EyeSys repeatability was 0.50 μm or better and was markedly better closer to the center of the cornea. ORBSCAN repeatability was between 1-2 μm for most of the cornea, including areas near the corneal center.

As was discussed in the methods section, EyeSys accuracy, that is, how correctly the surface elevation of a known surface is measured, was tested by measuring model corneas with known dimensions. Radially averaged EyeSys error as a function of distance from the corneal center was shown in Fig. 4. Figure 8 shows EyeSys measurement error for the test surface with 7.8 mm apical radius and shape factor p = 0.7, before compensation for known instrument error. Corneal zone diameter is 5.4 mm.

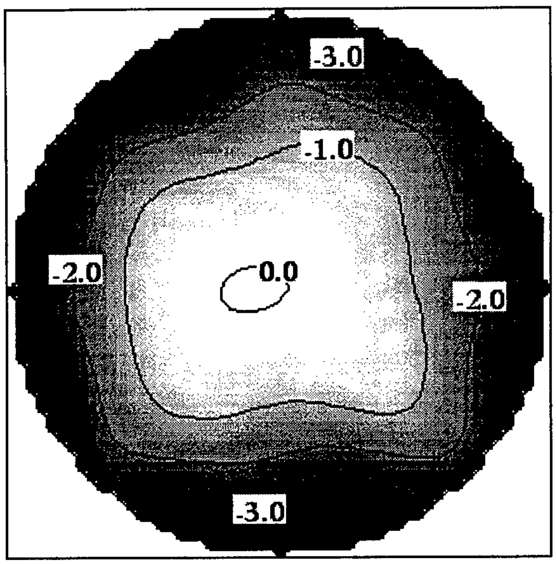

Figure 8. EyeSys surface elevation measurement error. Measurements were for a rotationally symmetric ellipsoid with apical radius of 7.8 mm and shape factor (p) of 0.7. Labels and contour lines show error in micrometers and the negative values show that the EyeSys underestimated the true surface elevations.

Figure 9 shows that, in comparison to Fig. 8, EyeSys accuracy was substantially improved after mathematically compensating for known instrument error (see Methods). Compensated EyeSys measurements were taken as the standard by which ORBSCAN accuracy would be measured. As with repeatability, accuracy with the EyeSys is best near the corneal center and gets worse peripherally. After compensation, EyeSys error is reduced to better than 0.5 μm across most of the 5.4-mm corneal zone.

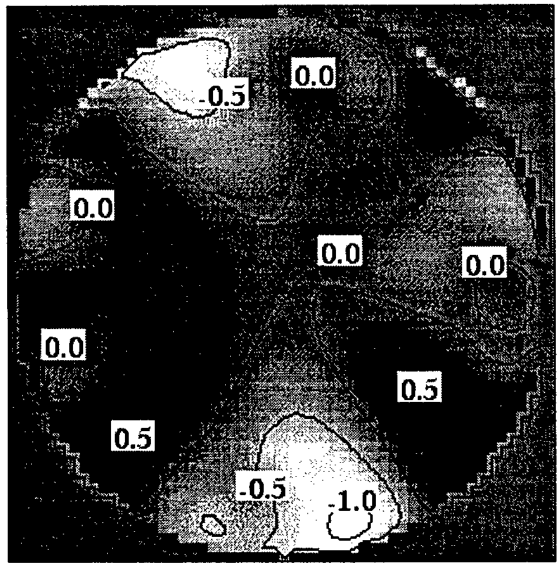

Figure 9. EyeSys surface elevation measurement error after correction for known instrument error. (This is the same ellipsoid as shown in Figure 8.) Labels and contour lines show error in micrometers.

ORBSCAN measurement error for the corneal front surface was defined as the difference between the mean ORBSCAN and EyeSys measurements (ORBSCAN minus EyeSys) for the same human cornea. As was described in the Methods section, the corneal topography measured by the EyeSys was interpreted as the true elevation contour, within the measurement accuracy of the EyeSys after compensation for instrument error (Fig. 9). Figure 10 shows ORBSCAN error in µm for a 5.4-mm diameter corneal zone. The negative values show that the ORBSCAN underestimated the surface elevations of the cornea, and the magnitude of the error was much larger than that of the EyeSys either before (Fig. 8) or after correction for instrument bias. Measurement error showed a steady increase from center to periphery, with maximum errors exceeding 10 µm.

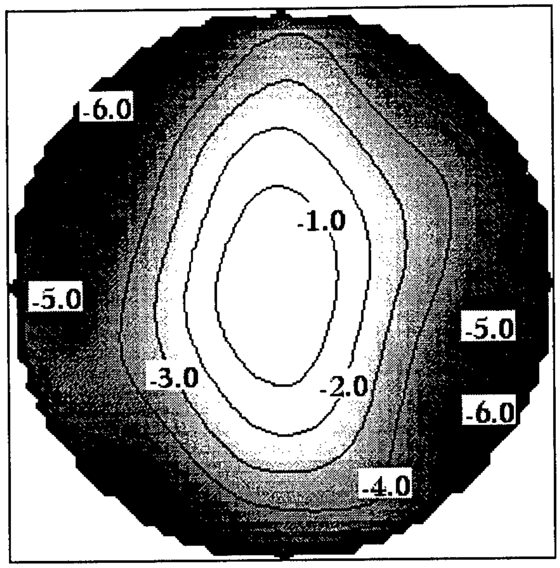

Figure 10. ORBSCAN measurement error. This error was defined as the mean ORBSCAN surface elevation measurement minus the EyeSys measurement for the same cornea. Labels and contour lines show error in micrometers, and the negative values show that the ORBSCAN underestimated the true surface elevations.

Radially averaged measurement error for the ORBSCAN was also computed and this was compared to the radially averaged EyeSys error (r=7.8 mm, p=0.7 surface) both before and after compensation for the EyeSys' systematic error. This is plotted in Fig. 11, and shows that the ORBSCAN error is much larger than both raw and compensated EyeSys data.

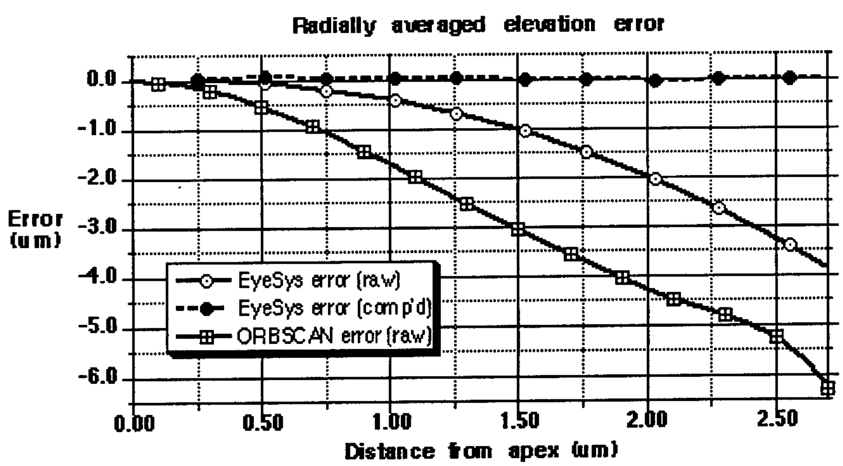

Figure 11. Comparison of radially averaged measuement error for the EyeSys (with and without compensation for instrument bias) and the ORBSCAN.

The errors shown in the two-dimensional error maps in Figs. 6-11 may be summarized by a single statistic for each map. One statistic is the maximum error; another is the root mean squared (RMS) error for each map, as defined in Eq. (14). Since each map represents values on a 0.1 mm square Cartesian grid, within a 5.4-mm corneal zone, each map contains n=2,289 data points. These statistics for repeatability and accuracy are summarized in Tables 3 and 4, respectively. Table 3 shows that the maximum value for the errors were similar for the two, but it gives an incorrect impression since, for most of the EyeSys repeatability map (Fig. 6), standard errors are less than 0.5 μm and the large value of 2.2 μm is only for a few data points in the inferior edge. The RMS error is a better statistic and shows that the EyeSys is about three times as precise (repeatable) as the ORBSCAN. Similarly, the RMS statistic in Table 4 gives a better comparison of accuracy with the two instruments. After compensation, the EyeSys error was nearly one tenth that of the ORBSCAN.

$$\text{RMS error} = \frac{\sqrt{\sum_i^n \left(\text{error}_i^2\right)}}{n}$$

Table 3.
Repeatability for the EyeSys and ORBSCAN.

Instrument	**Max stderr (μm)**	**RMS stderr (μm)**
ORBSCAN	2.1	0.03
EyeSys	2.2	0.01

Note: Maximum and RMS standard errors for the EyeSys and ORBSCAN for 16 repeated measurements each, of the same human cornea. Values are in micrometers.

Table 4.
Accuracy of the EyeSys and ORBSCAN (in micrometers).

Instrument	**Max error (μm)**	**RMS error (μm)**
EyeSys (raw)	-4.6	0.05
EyeSys (compensated)	-1.1	0.01
ORBSCAN	-7.7	0.09

Note: Maximum and RMS measurement error for the EyeSys without compensation for systematic instrument error (row 1) and with compensation (row 2), when tested against a calibration surface with r=7.8 mm and p=0.7. Maximum and RMS measurement error for the ORBSCAN, when tested against compensated EyeSys measurements of a human cornea. Values are in micrometers.

Discussion

Both the ORBSCAN and EyeSys underestimated surface elevation, and errors increased peripherally. Without correcting the EyeSys data for systematic instrument bias, both the ORBSCAN and EyeSys showed a magnitude of measurement error that was much greater than what we require for detailed studies of cornea optics. The ORBSCAN error was generally twice as large as the raw EyeSys error. After compensation for known instrument error, EyeSys accuracy improved substantially, and this improves the accuracy of this videokeratoscope to the desired level (< 1 μm error) within most of the 5.4-mm diameter corneal zone. The EyeSys was also about three times more precise than the ORBSCAN for repeated measurements of a normal human cornea.

This initial study of ORBSCAN accuracy was limited to a single cornea and shows the magnitude of ORBSCAN error if the instrument is used as is (without modifying the raw data) from the manufacturer. If a larger number of corneas, representing a broad range of cornea shapes, were measured, it would be possible to better analyze the nature of the ORBSCAN's error. It might be possible to compensate for some systematic bias and improve accuracy as we did with the EyeSys. Until this is done, or until the manufacturer changes the instrument to significantly improve accuracy, the ORBSCAN is not accurate enough to use for studies of subtle corneal optical aberrations.

Data for this study were collected in March of 1999. Since then, ORBTEK has introduced the ORBSCAN II, an improved version of the instrument evaluated in this study. The ORBSCAN II adds a videokeratoscope to the slit-scan system, and corneal topography measurements are based on data acquired from both systems. Since the EyeSys (a videokeratoscope) proved to be more accurate than the ORBSCAN, the ORBSCAN II may have much better accuracy that the first generation instrument we evaluated. A future study should, therefore, evaluate the accuracy of the ORBSCAN II using a wide range of corneas, and it should also compute the repeatability of back surface and corneal thickness measurements. If it were able to demonstrate sub-micron accuracy across most of the cornea, the ORBSCAN would prove to be a very valuable instrument for visual optics research.

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